Introduction

The introduction is in two parts. The first part deals with the rationale and goals of the study. The second part is an overview of the analytical approach and main data sets.

1.1 Background and objectives

Global mariculture production totalled 36.1million tonnes with a value of US$37.9 billion in 2010 (FAO Statistics and Information Service of the Fisheries and Aquaculture Department, 2012). Mariculture is an important part of aquaculture, accounting for about one-half in production by weight. Nearly all of global mariculture is actually inshore mariculture that is mariculture that is situated or carried out near the shore. For example, a Google Earth-based study of the spatial distribution of fish cages and pens among 16 countries in the Mediterranean showed that 80 percent of these installations were within 1 km of the coast and that the maximum distance offshore was about 7 km (Trujillo, Piroddi and Jacquet, 2012). Generally, inshore mariculture production is well established in protected coastal locations, in shallow waters with low hydrodynamic energy, and in areas that are in close proximity to supporting infrastructure (Olsen *et al.*, forthcoming). Mariculture production consists of fish, invertebrates and aquatic plants, with the plants accounting for about one-half of the weight. In contrast, offshore - or open ocean mariculture - is in its infancy and production is almost exclusively made up of fish and shellfish. Mariculture is moving offshore using two approaches: one of which is the development of more robust versions of existing inshore culture technologies, and the other of which is through the development of novel culture systems that can be submerged to avoid the winds and waves characteristic of offshore areas (Jeffs, forthcoming).

A number of definitions have been proposed for offshore aquaculture, and the problem of defining the term "offshore" in relation to mariculture development has been discussed at length by Lovatelli and Aguilar-Manjarrez (forthcoming). However, for the purposes of this technical paper, the definition proposed by Drumm (2010) (Box 1) is adequate and is consistent with the assumptions and criteria for offshore mariculture development set out in Section 1.2.

BOX 1

Definition of offshore aquaculture

"In general Offshore Aquaculture may be defined as taking place in the open sea with significant exposure to wind and wave action, and where there is a requirement for equipment and servicing vessels to survive and operate in severe sea conditions from time to time. The issue of distance from the coast or from a safe harbour or shore base is often but not always a factor".

Source: Drumm (2010).

At local and national levels, the drivers for the expansion of mariculture from existing inshore areas to offshore waters are the competition for space, frequent negative public perception and quality of the environment. Looking to the future, the development of offshore mariculture can be justified on the basis of the need to provide food security in the face of the projected increase of world population. Viewing the oceans as contributing to future food security is in line with the conviction that the potential of the world's oceans to supplement the food supply is vastly underutilized (inter alia, Forster, 2007). As pointed out by Forster (2011a; forthcoming), only 1.7 percent of the world's total food tonnage comes from the ocean, an area covering about 70 percent of the Earth. Of that, less than 0.5 percent is from mariculture.

There has been interest in expanding aquaculture to offshore areas for decades (for example, Hanson, 1974; Wilcox, 1982; Ryan, 2004; Lee and O'Bryen, 2007a; Benetti and Welch, 2010; Simpson, 2011). Recognizing the need to assess the possibilities for the development of offshore aquaculture, the FAO Fisheries and Aquaculture Department conducted a workshop on offshore mariculture. Thus far, the outputs of the workshop include: workshop proceedings, a global review prepared by Olsen (forthcoming), six technical reviews, and a strategic framework for mariculture development that includes recommended actions by FAO (Olsen *et al.*, forthcoming). The strategic framework recognizes that FAO can guide and support Member States and industry in the development needed for expanding mariculture to offshore locations.

The technical papers presented in the workshop proceedings (Lovatelli and Aguilar-Manjarrez, forthcoming) include: technical constraints, opportunities and needs to ensure the development of the mariculture sector worldwide in the tropical zone (Jeffs, forthcoming) and in the temperate zone (Forster, forthcoming), a review of environmental and ecosystem issues and future needs for the tropical zone (Angel and Edelist, forthcoming) and for the temperate zone (Holmer, forthcoming), governance in marine aquaculture: the legal dimension (Percy, Hishamunda and Kuemlangan, forthcoming), and mariculture development economics (Knapp, forthcoming). Spatial perspectives on offshore mariculture potential related to the workshop proceedings were presented by Kapetsky and Aguilar-Manjarrez and are summarized in Olsen *et al.*, forthcoming.

Recently, the Aquaculture Forum Bremerhaven conducted a workshop on the future of global open ocean aquaculture development that resulted in the Bremerhaven Declaration (Anon., 2012). The Declaration lays out recommendations and their justifications in nine subject areas. Those most pertinent to this technical paper are a global strategy for sustainable open ocean aquaculture development, the urgent need to plan for the comprehensive development of land- and water-based infrastructures and that priority should be given to the culture of species well-established in aquaculture.

Spatially derived estimates are essential to define locations and quantify expanses of areas suitable by species and culture systems for offshore mariculture development. Furthermore, many of the issues and opportunities associated with the development of offshore mariculture have components that can be addressed separately, or together, using spatial analyses. In particular, spatial analysis lends itself to the integration of technical, economic, environmental and jurisdictional problems of mariculture development, all of which are addressed in this technical paper.

This paper was inspired by the perception that there were few studies dealing specifically with the spatial aspects of offshore mariculture potential, particularly from global and national perspectives. Among the studies addressing the spatial aspects of offshore mariculture at subnational levels, zones suitable for mariculture were identified in the Region of Murcia, the Kingdom of Spain, using water depths between 35 and 50 m and distances that extend up to 15 km from the shore as basic criteria while considering other uses (Servicio de Pesca y Acuicultura, 2000). In a similar study, zones suitable for mariculture in waters up to 50 m depth were identified for Andalucia, the Kingdom of Spain (Macias-Rivero, Castillo y Rey and Zurita, 2003). Also in the Kingdom of Spain, Pérez, Telfer and Ross (2005) focused on developing a methodology for selecting suitable sites for offshore farming of seabream (*Sparus aurata*) and seabass (*Dicentrarchus labrax*) in floating cages in Tenerife Island, Canary Archipelago. A preliminary analysis of coastal zone management issues (e.g. fisheries, salmon culture, ecologically sensitive areas) related to the feasibility of open ocean farms in the Bay of Fundy, Canada, was made by Chang, Page and Hill (2005). A first step towards assessing potential sites for offshore aquaculture development in western Ireland was based on a minimum depth of 20 m, shelter from ocean swell and proximity to landing facilities. Of the 46 sites evaluated, at the five most promising sites depth ranged from 27 to 40 m, distance to landing facilities ranged from 6 to 28 km and shelter ranged from moderately exposed from one cardinal point of the compass to exposed from two cardinal points (Watson and Drumm, 2007).

Longdill, Healy and Black (2008) determined the suitability of offshore open coast locations (from the coast to 100 m water depth) for commercial bivalve culture of the New Zealand (or greenshell) mussel (*Perna canaliculus*) within the Bay of Plenty, New Zealand. Kapetsky and Aguilar-Manjarrez (2007) carried out a reconnaissance study of open ocean aquaculture potential of cobia (*Rachycentron canandum*) in cages and blue mussel (*Mytilus edilus*) on longlines in the eastern exclusive economic zones[1] (EEZs) of the United States of America; they later expanded the study to include Atlantic salmon (*Salmo salar*) and the integrated multitrophic aquaculture (IMTA) of Atlantic salmon with blue mussel within the same EEZ area (Kapetsky and Aguilar-Manjarrez, 2010). Gifford, Benetti and Rivera (2007) explored the development of a Caged Aquaculture Suitability Index dedicated to optimally locating caged aquaculture projects planned for offshore Florida (United States of America), the Commonwealth of Puerto Rico, and the United States Virgin Islands. Rester (2009) and the Gulf of Mexico Fishery Management Council and the National Marine Fisheries Service (2009) selected suitable sites for offshore cage aquaculture in the United States of America portions of the Gulf of Mexico in waters from 25 to 100 m in depth with indigenous fish species in mind; species, however, were not individually analysed. A broadly based study for the development of open ocean shellfish farming in the Bay of Biscay included analyses relating to user conflicts, technologies and operational requirements, a wide range of criteria relating to site selection, market analysis and business models (Mendiola *et al.*, 2012; Mendiola and Galparsoro, forthcoming).

The present study builds on previous experience with spatial analysis of offshore mariculture potential and expands the scope from subnational levels to a global perspective. Thus, the main objective of this study is to provide measures of the status and potential for offshore mariculture development from a spatial perspective that are comprehensive of all maritime nations and comparable among them. The results are a gauge, from a spatial perspective, of the indicative near-future global and national potential for the expansion of mariculture from current inshore locations to offshore areas. The results are also meant to stimulate interest in national-level assessments of mariculture potential, which would include more criteria and higher resolution data than in this technical paper. An additional objective is to identify nations that appear to have high potential but that are not yet practising mariculture.[2] With these objectives in mind, the study is aimed at decision-makers of international organizations and at all levels of governmental administrations involved with aquaculture development as well as at entities in the commercial sector involved with mariculture services and development.

1.2 Overview of the analytical approach and outputs

The objective of this section is to briefly introduce the framework of the analyses without going into the methods in the detail that would be required to repeat the study. For that purpose, the analytical procedures and the data sources are set out in Annex 1.

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[1] An exclusive economic zone (EEZ) is a concept adopted at the Third United Nations Conference on the Law of the Sea (1982), whereby a coastal State assumes jurisdiction over the exploration and exploitation of marine resources in its adjacent section of the continental shelf, taken to be a band extending 200 miles from the shore (OECD, 2012).

[2] Mariculture countries for the purposes of this study are those listed in the FAO aquaculture production statistics (FAO Statistics and Information Service of the Fisheries and Aquaculture Department, 2010) as having mariculture production in one or more years for the period 2004–2008.

This section provides an account of the development of the analytical approach. In a stepwise fashion, key assumptions about the near-future development of offshore mariculture and some of its salient features provide a foundation for the analyses. The key assumptions are used to identify the analytical criteria. With the analytical criteria identified, numerical thresholds for each criterion are established based on mariculture practice, and the thresholds are then used in spatial analysis to identify locations and to quantify area expanses of various kinds of offshore mariculture potential for each maritime nation.

1.2.1 Key assumptions on the spatial development of offshore mariculture

Key assumptions have been made about where and under what conditions the spatial development of offshore mariculture will take place for the next five to ten years. The assumptions are based on the technical characteristics of inshore and offshore culture installations, and on the aquatic animal species grown out inshore and in the relatively few commercial ventures already established in offshore areas. The near-future assumptions are supported by expert reviews (Lovatelli and Aguilar-Manjarrez, forthcoming) and a synthesis of them (Olsen *et al.*, forthcoming), and/or are the perceptions of the authors of this technical paper (Box 2).

In spatial terms, it is assumed that near-future offshore mariculture development will take place within EEZs and that, initially, offshore sites will be in close proximity to onshore service facilities. That offshore mariculture will be in close proximity to coastlines is due to a variety of technical and economic limitations, all of which relate to the need to tether culture installations to the seafloor, to the costs of maintaining onshore and offshore facilities, and to the requirement for frequent commuting between them (Box 2). Offshore aquatic plant mariculture was not considered here because of a lack of criteria for offshore culture installations for plants.

BOX 2
Key assumptions about the near-future development of offshore mariculture

Near-future offshore mariculture development will:

- mainly take place within exclusive economic zones in order to ensure national governance over development and management and to provide for the legal protection of investors.
- mainly use cages for fish and longlines for molluscs as culture systems:
  - relatively close to coastlines because of the depth-associated costs of tethering culture systems to the seafloor in relatively shallow coastal waters;
  - limited by technical constraints on mariculture system installation, maintenance and endurance related to the depth of tethering.
- be dependent on onshore facilities:
  - to support offshore grow-out installations (e.g. feed, holding seed, storage, maintenance, set-up for processing and transporting harvested animals);
  - protected from storm damage and with reliable access to the offshore grow-out sites;
  - in close proximity to offshore sites in order to minimize distance-related costs of transport services.
- mainly employ species with already proven culture technologies and established markets.
- compete and conflict with some other uses of ocean space, but will be complementary with others.

1.2.2 Criteria and thresholds used to estimate near-future offshore mariculture potential

This section relates the basic criteria on the near-future spatial development of offshore mariculture to the thresholds that are at the core of the estimates of potential for offshore mariculture development. The criteria to estimate offshore mariculture potential (Table 1) follow from the key assumptions about offshore mariculture development set out in Box 2. These criteria are then related to the various kinds of offshore areas that they represent and to the thresholds that pertain to those areas (Table 1).

TABLE 1
Criteria and corresponding threshold ranges used to estimate near-future offshore mariculture potential

Criteria	Areas with offshore mariculture potential	Thresholds
1. Boundaries of the EEZs of sovereign nations.	Area for offshore development within sovereign national legal jurisdictions.	EEZs up to 200 nm (370.4 km) offshore.
2. Depth and current speed as the fundamental criteria characterizing the technical limits of present offshore submerged cage and longline culture systems.	Areas in which it is technically feasible to place culture installations.	Depth for cages and longlines: 25–100 m. Current speed for cages and cultured animals: 10–100 cm/s.
3. Distance offshore from onshore infrastructure related to economic cost limits on transportation and on reliable access from a port to the sea.	Areas in which it is cost-effective to place culture installations based on distance-related costs and on reliable access from shore to sea.	Cost-effective area for development: area within 25 nm (46.3 km) of a port, with ports defined by the World Port Index (2009).
4. Reliable access between shore and offshore facilities assumed; proximity of offshore culture sites to the shoreline not limited tothe cost-effective area for development.	Areas with potential within EEZs, but presently outside of cost-effective areas for development.	All thresholds other than the cost-effective area for development apply.
5. Favourable offshore grow-out environment based on temperature requirements of representative fish and mussels and on food availability measured as chlorophyll concentration for the latter.	Areas with favourable grow-out environments for fish and mussels.	Temperatures: – Cobia: 22–32 °C – Atlantic salmon: 1.5–16 °C – Blue mussel: 2.5–19 °C and Chlorophyll-*a* > 0.5 mg/m^3 – IMTA: 2.5–16 °C and chlorophyll-*a* > 0.5 mg/m^3
6. Competing, conflicting and complementary uses of ocean space.	Areas with potential lost because of competing and conflicting uses of marine space.	Areas with potential for cobia hypothetically excluded from marine protected areas.

EEZ boundaries to define the spatial limits for near-future offshore development

One of the key assumptions is that near-future offshore mariculture will be developed within the EEZs of sovereign nations (Box 2). The boundaries of EEZs, therefore, provide a spatial framework within which to assess the amount of national area with offshore mariculture potential (Table 1). EEZ boundaries were defined using the Flanders Marine Institute (VLIZ) Maritime Boundaries Geodatabase (Flanders Marine Institute, 2012; Annex 1, Table A1.1). Thus, the term "offshore mariculture potential", for the purposes of this technical paper, resides within the area bounded by EEZs, usually from 3 to 200 nm (5.5–370.4 km) from the shoreline. Offshore mariculture potential in this technical paper is expressed quantitatively as the surface area in square kilometres within EEZs in each sovereign maritime nation meeting various fundamental criteria and their associated thresholds (Table 1).

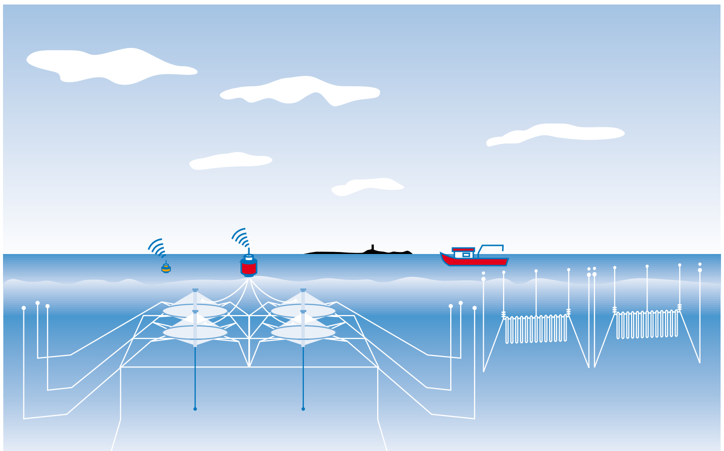
Depth and current speed to define the spatial limits on offshore cages and longlines

Sea cages for fish grow-out and longlines for mussel grow-out are the prevalent culture structures in current offshore mariculture practice (Figure 1). Both sea cages and longlines are tethered to the seafloor. This is the basis for the key assumption that both sea cages and longlines will be located close to coastlines for the near future because of technical and cost limits related to the depth of tethering (Table 1). It assumed that both of these culture systems will be submerged to avoid threatening sea conditions, such as the one depicted in Plate 1, or much worse.

Along with depth, current speed is another fundamental criterion that dictates the offshore space in which sea cages and longlines can be installed (Table 1; Figure 2). Depth affects the size of the seafloor footprint for typical multi-anchor cage systems as well as capital, installation and maintenance costs for the anchoring system (Browdy and Hargreaves, 2009). Current speed affects both the design of offshore installations as well as the growth-related conditions of cultured organisms in or on them in many ways, as shown in Figure 2.

Depth thresholds for sea cages and longlines, 25–100 m (Table 1), were established based on manufacturer specifications and on actual mariculture practice (Annex 1, Table A1.2). Similarly, the current speed threshold (Table 1) was based on the same sources, but also was considered in terms of effects on cultured fish and shellfish (Annex 1, Table A1.3a and A1.3b).

FIGURE 1
Sea cages and longlines for offshore mariculture



Source: NOAA (2011).

FIGURE 2
Effects of current speed on culture structures and on cultured organisms

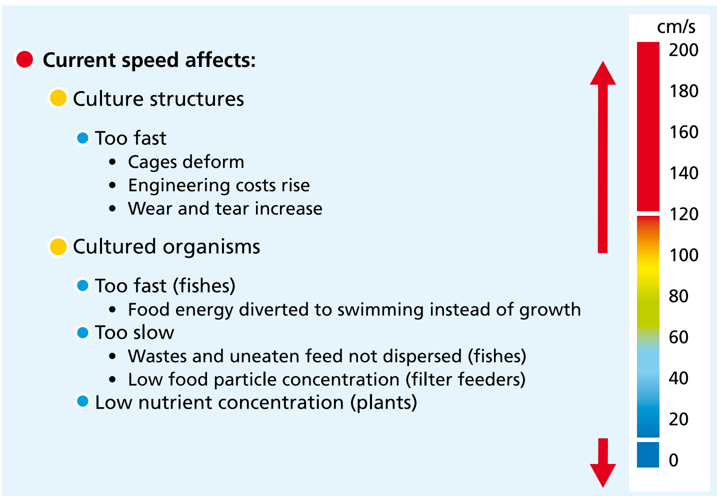


PLATE 1
Fish cages in rough weather in Norway

COURTESY OF AKVA GROUP

Note: Square plastic collar gravity cage in rough conditions, Kingdom of Norway. Polarcirkel, Kingdom of Norway.

Distance from a port and reliable offshore access to spatially define the cost-effective area for offshore mariculture development

A key assumption for near-future offshore mariculture is the dependence, in numerous ways, of offshore development on shoreside support facilities (Box 2; Nash and Fairgrieve, 2007; Lee and O'Bryen, 2007b).

Operational and service activities offshore have their complementary activities at shore support facilities that include, for example, office space, warehousing feed and equipment, and holding facilities for stock destined for grow-out and harvested products. An important aspect of this dependence is the need for offshore installations to be positioned relatively close to onshore facilities so as to minimize distance-related costs of transport and maintenance services. A closely related aspect of this dependence is the need for reliable access from the shore facility to the offshore site in order to carry out routine operations and to deal with emergencies (Box 2). The dependence between the onshore and offshore locations can be defined succinctly as two criteria with which to spatially estimate offshore mariculture potential: the reliable access from shore to offshore and the distance-related costs between shore and offshore (Table 1).

Access from a shore support facility to an offshore mariculture installation was considered an indispensable criterion for assessing potential by Kapetsky and Aguilar-Manjarrez (2007) owing to the numerous operational and service activities that must be carried out on sea cages (e.g. Table 7 in Huguenin, 1997). Access also figures prominently among offshore aquaculture site selection criteria (Benetti *et al.*, 2010). The other criterion, this one with an economic basis, relates to travel time and distance from an onshore support facility to an offshore grow-out installation. Twenty-five nautical miles (46.3 km) was the maximum cost-effective distance from onshore to an offshore culture installation found by Jin (2008) in a study of economic potential of offshore aquaculture operations that included grow-out of Atlantic salmon. The 25 nm (46.3 km) distance has been adopted for this technical paper. The criteria of reliable access and the 25 nm cost-effective distance were combined into a single criterion termed the "cost-effective area for offshore mariculture development". It is defined spatially as the surface area within a 25 nm radius of a port. Ports were those identified in the World Port Index (2009) database (Table 1; Annex 1, Table A1.1).

Offshore mariculture potential within EEZs that is presently outside of cost-effective areas for development

Despite the assumed need to take into account the economic consequences of distance-related costs in estimating potential, there is another near-future situation that must be spatially defined: coastline locations with identified proximate offshore potential but lacking the adjacent ports that have been identified in the World Port Index (2009) database. This has been envisioned in a recent definition of offshore aquaculture (Drumm, 2010; Box 1). It implicitly takes into account the many situations where shoreside facilities and access to the sea are adequate to support offshore installations, but where the World Port Index (2009) database of ports is incomplete. This situation is likely to pertain to developing countries, as well as to developed countries with minor ports. In terms of assumptions and criteria to assess offshore mariculture potential, this situation corresponds to those areas that are technically feasible for offshore mariculture development (i.e. with suitable depths and current speeds for cages and longlines), but outside of the cost-effective area for development (Table 1).

Offshore mariculture potential of three representative species and IMTA of two of them spatially defined by environments favourable for grow-out

The assumption regarding the species that will be important in the immediate future of offshore mariculture states that the species will be mainly those with proven culture technologies and with established markets (Box 2). Many species have been suggested as candidates for mariculture depending on the region of interest, and some of the species are already cultured offshore or are undergoing trials. Including all of the animal species with proven culture technologies and established markets was beyond the scope of this technical paper, and thus three representative species were selected. The species were cobia (*Rachycentron canadum*), Atlantic salmon (*Salmo salar*) and blue mussel (*Mytilus edulis*) (Plate 2).

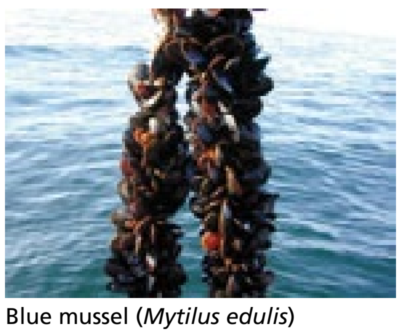
PLATE 2
Species indicative of different kinds of offshore mariculture potential

COURTESY OF IOUTDOOR

Cobia (*Rachycentron canadum*)

COURTESY OF CORNELL UNIVERSITY

Atlantic salmon (*Salmo salar*)



COURTESY OF NOAA

Blue mussel (*Mytilus edulis*)

Each species is indicative of a different kind of offshore mariculture potential. Criteria for the selection of these species have already been covered by Kapetsky and Aguilar-Manjarrez (2007, 2010), and the same criteria have been employed herein. Multi-country production[3] is indicative of viable technologies and established markets. Global marine mariculture production and value for 2010 were 1.4 million tonnes and US$7.8 billion for the Atlantic salmon, 2 088 000 tonnes and US$349 million for the blue mussel, and 41 000 tonnes and US$71 million for the cobia (FAO Statistics and Information Service of the Fisheries and Aquaculture Department, 2012). Cobia is among seven fish species in the tropical zone identified by Jeffs (forthcoming) with offshore mariculture potential. Additionally, cobia is currently being cultured in a number of offshore locations (see Chapter 5) and in many inshore locations in the People's Republic of China, the main producing country. An additional advantage that the cobia has over other species is that it has a global distribution. Therefore, its culture offshore for many nations would not involve importing an exotic species. Ryan (2004) and Watson and Drumm (2007) identify open ocean sites for offshore grow-out of Atlantic salmon in Ireland, and Jackson (2007) states that 30 percent of Ireland's farmed salmon come from sites with moderate exposure. Likewise, there are many Atlantic salmon culture sites with partial shelter near the open sea in the Kingdom of Norway (Chapter 5). The blue mussel has been farmed experimentally offshore with encouraging results in the northeastern United States of America (Langan and Horton, 2005; NOAA, 2005) and on a semi-commercial subsidized basis through several initiatives in the same area (Atlantic Marine Aquaculture Center, 2007; Zeiber, 2008). The blue mussel is being assessed for offshore culture in the Federal Republic of Germany in connection with wind farm installations (Buck, 2011).

The species selected as measures of offshore mariculture are representative in several ways of fish and mussels that may eventually figure importantly in offshore mariculture. In this regard, cobia and Atlantic salmon are generic indicators of offshore mariculture potential that are in the category of "fed" mariculture. Both are grown out in sea cages (Plate 3). The blue mussel is indicative of potential for bivalve mussels grown on longlines in cool temperate waters. Being a filter feeder, it exemplifies "extractive" mariculture. This latter criterion enabled estimating potential of not only each of the individual species, but also for estimating the integrated potential of two of them (Atlantic salmon and blue mussel) for potential in IMTA (Figure 3). IMTA has been reviewed from a global viewpoint by Soto (2009).

The three species, taken together, are surrogate indicators of offshore mariculture potential of species with similar temperature thresholds favouring grow-out and, in the case of the mussel, with similar food availability requirements. From a global viewpoint, the growth-temperature

PLATE 3
Example of fed aquaculture of fish in cages

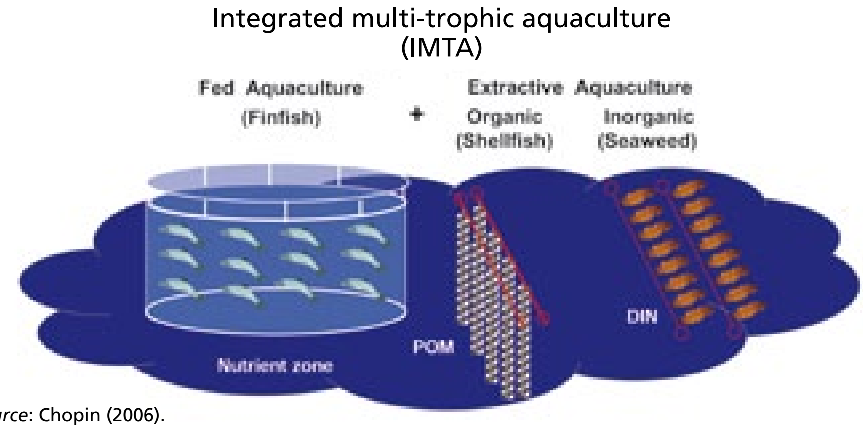
COURTESY OF F. CARDIA

[3] If the fish or shellfish is cultured in several countries, technical expertise and markets are available.

FIGURE 3
Integrated multi-trophic aquaculture in practice and in concept

Salmon (left), mussels (right foreground) and seaweeds (right background) integrated multi-trophic aquaculture (IMTA) in the Bay of Fundy, Canada

Conceptual diagram of an integrated multi-trophic aquaculture (IMTA) operation combining fed aquaculture (finfish) with organic extractive aquaculture (shellfish), taking advantage of the enrichment in particulate organic matter (POM), and inorganic extractive aquaculture (seaweeds), taking advantage of the enrichment in dissolved inorganic nutrients (DIN)



Source: Chopin (2006).

thresholds collectively span all climate zones in which most mariculture takes place: cold and cool temperate for the Atlantic salmon and blue mussel, and tropical and subtropical for the cobia. General information, specifically on the culture of these species, can be obtained through the FAO Cultured Aquatic Species Information Programme (FAO, 2012).

Offshore mariculture potential of these species was based on criteria that could be used to locate areas that would be favourable for grow-out. It is well known that temperature affects the feeding, growth and metabolism of fish and shellfish. Thus, water temperature was the criterion applied to all three species. As an illustration, the apparent effects of water temperature on the duration of grow-out of Atlantic salmon to a harvestable size among four salmon-producing nations are shown in Annex 2. Water temperature, salinity, food quantity and quality are the most important factors affecting grow-out time of mussels (Langan and Horton, 2005). In this regard, chlorophyll-*a* concentration was used as an indicator of food availability to sustain the filter-feeding requirements for blue mussel grow-out. The temperature and chlorophyll-*a* thresholds that were used to locate areas with potential for favourable grow-out (Table 1) were obtained from reviews of the literature and through correspondence with researchers and aquaculture practitioners (Annex 1, Tables A1.1 to A1.4c).

Spatial data acquired through satellite remote sensing were indispensable for this study. The temperature and chlorophyll-*a* data used to identify areas with potential for good growth were taken from monthly archives. The archived data were used in two ways. The first way was to analyse the data to identify all of the areas meeting suitability thresholds; the second way was via parameter retrieval to estimate temperatures and chlorophyll-*a* concentrations at specific mariculture locations as part of the verification process. Annex 3 entitled "Remote sensing for the sustainable development of offshore mariculture" was paired with this technical paper in recognition of the importance of remote sensing to mariculture. This importance is not only as a source of data for spatial analyses to assess potential as was the use herein, but also for spatial analysis for zoning and siting, as well as for operational remote sensing to aid mariculture management. The close relationship between spatial analysis for aquaculture and remote sensing of environmental variables is also described by Dean and Popolus (2013).

Identifying competing, conflicting and complementary uses of ocean space

At first glance it may appear that the space for the development of offshore mariculture is limitless. However, especially near to shore, there are many possible competing, conflicting or complementary uses of ocean space. Many such areas are defined locally, and to deal with them individually is beyond the scope of this technical paper. Nevertheless, a possible competing offshore use is marine protected areas (MPAs). MPAs were selected because the database is global and because MPAs can be both national and international in scope. The other use criterion was illustrated by estimating the area that would be lost by hypothetically excluding open ocean mariculture of cobia in MPAs, with MPAs defined by the International Union for Conservation of Nature (IUCN) and the United Nations Environment Programme-World Conservation Monitoring Centre (UNEP-WCMC) (2010).

1.2.3 Comparisons of predicted offshore potential with inshore mariculture practice and verifications at offshore mariculture sites

Ideally, results are verified; however, verification was difficult because the predictions of offshore mariculture potential are for an industry that largely does not yet exist. Nevertheless, the predictions of potential were tested by making three kinds of comparisons based on the offshore potential found for each of the three species-culture system combinations. The comparisons were:

(i) **Potential compared with production:** These were comparisons of offshore mariculture potential in square kilometres with the mariculture production of nations actually practising mariculture of that species-culture system combination at the national level. The rationale for a positive result from this comparison is simply that where mariculture already exists there is an advantage to its further development. Mariculture already in practice in a nation with the species used in this technical paper is indicative of established infrastructure, goods, services, juvenile production and other technologies, as well as access to markets to support offshore development.

(ii) **Offshore mariculture potential compared with inshore mariculture locations:** These were comparisons on maps at the national to local level of areas found to have offshore potential compared with the actual locations of inshore mariculture installations of those species, or with inshore farming areas in which mariculture of those species was being practised. The rationale for an advantage in the development of offshore mariculture in the areas where there is a correspondence between offshore potential and inshore practice is the same as for the national- level comparison above, but with the advantage of inshore practice being proximate to offshore areas with potential for development.

(iii) **Offshore mariculture potential compared with actual offshore mariculture locations:** These were comparisons on maps of local areas with offshore mariculture potential with the actual locations of offshore installations. These comparisons are the actual verification of the results.

1.2.4 Basic requirements and constraints on the study

The basic requirements of this study were that the results had to be comprehensive of all maritime nations whether or not they were practising mariculture and that they had to be comparable among them. The estimates of offshore potential were to be expressed separately for mariculture-practicing nations and those nations yet to develop mariculture in two ways: aggregated globally and at the national level. The summary tables of the results of the spatial analyses presented in Olsen *et al.* (forthcoming) express the results in terms of potential in relation to climate zones. However, for this technical paper, while climate zones are retained as layers in the map figures as a link to the earlier results, the focus is on offshore mariculture potential by sovereign nation with the results ranked and reported for the top 20 among mariculture nations and non-mariculture nations alike. The terms “mariculture nations” and “non-mariculture nations” are a concise way of designating nations that already practise mariculture and those nations not yet practising mariculture. The boundaries of sovereign nations were taken from the GADM database of Global Administrative Areas (2009) described in Annex 1, Table A1.1.

One of the self-imposed constraints on this technical paper was that all of the data had to be freely downloadable from the Internet so that, ideally, anyone could repeat or expand the analyses herein. These data sets are described in Annex 1, Table A1.1. Also, many of the key spatial data sets derived from the original sources for this study can be downloaded from the FAO Geonetwork (www.fao.org/geonetwork/srv/en/main.home).

Another constraint was that all of the spatial analyses had to be accomplished on desktop computers using readily available geographic information system (GIS) software to allow for replication or expansion. This constraint was met except for the current speed analyses. It was necessary to have the original current data sub-sampled and extracted from the HYbrid Coordinate Ocean Model (or HYCOM) current speed model (Annex 1, Table A1.1) before they could be transferred to the desktop computer workstations for final analyses. Manifold (CDA International Ltd.) and ArcGIS 9.3 (ESRI – Environmental Systems Research Institute) were the GIS software used, the latter for the more complex, repetitive and time-consuming analyses that were conducted using custom Visual Basic for Applications (VBA) functions within ArcGIS 9.3, culminating as shapefiles[4] that were then analysed in Manifold. Results of spatial analyses were exported to Microsoft Excel 2010 in which they were reported using pivot tables and pivot charts. Offshore mariculture potential was reported as maps showing the areas with potential, tables that presented surface areas in aggregate globally, and charts with potential ranked by the main nations, usually 20 in number, meeting various criteria.

[4] A shapefile is a digital vector storage format for storing geometric location and associated attribute information.